

# ELLIPTICAL GALAXY DYNAMICS: THE ISSUES PERTAINING TO GALAXY FORMATION

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## Abstract

How elliptical galaxy dynamics relate to galaxy structure, stellar populations, spiral galaxies and environment are reviewed. The evidence assembled shows that most, if not all, galaxies originally classified as gE contain disks within them. Taken together, the existing evidence are most consistent with the gravitational, hierarchical, clustering, merging (HCM) concept that all galaxies, including gE, are formed from the combination of much smaller galaxies. Within the HCM picture, the evidence also strongly suggests that the subunits which go into forming galaxies must be related in specific ways both to the mass of the galaxy they will form, and to the environment in which the galaxy forms. Despite the extensive data that we now have on galaxies that can constrain their formation history, the lack of a physical understanding of the stellar initial mass function prevents us from developing realistic physical models for galaxy formation.

## 1 Introduction

Recent reviews on the dynamics of elliptical galaxies *per se* have been given in the last several years by [21], [15], [25], [1], [18]. Each of those reviews covers a difference aspect of the wealth of information we now have, both observational and theoretical, on the detailed structures of elliptical galaxies. Yet, that informaton is only part of the story we need to know if we are ever to fully understand galaxy formation in general, and the formation of elliptical galaxies in particular. To this detailed information we have to add evidence on how the dynamics of ellipticals are related to their stellar populations, to the dynamics of spiral galaxies, and to their environment. To this evidence we have to also understand the physics that underly star formation in general, and the existence of a well-defined stellar initial mass function in particular. As we will discuss in this review, even what we call an “elliptical galaxy” is no longer clearly defined, as detailed photometric and dynamical studies are finding disks in most “giant elliptical” galaxies.

This review uses existing evidence in the literature, supplemented by the results from the author’s participation in the EFAR survey ([31], [32], [27], [28], [12]), and from the existing information on the distribution of nearby galaxies. The discussion will be divided into six parts: a brief summary of the dynamics and structure of giant elliptical (gE) and S0 galaxies; the relationship of stellar populations to dynamics and structures of E galaxies in general; presence or absence of disks in gE galaxies plus some of the kinds of disks seen in gE galaxies; the relationships among gE, S0, spiral galaxy dynamics; the environments in which we find gE and S0 galaxies near us; and a discussion of what new perspectives we might extract from this evidence regarding galaxy formation.

## 2 Dynamics and Structure

Ever since it was discovered that giant elliptical (gE) galaxies do not rotate to support their observe flatness (e.g., [6]), their internal dynamics have been interpreted in terms of anisotropic velocity dispersions resulting in intrinsically triaxial figures (e.g., [7]). As Merritt ([21]) summarizes in the most recent extensive review on this subject, our knowledge of the dynamical structure of gE galaxies is based both on theoretical models of this structure and on detailed studies of individual galaxies.

All of these studies indicate that gE galaxies can have a wide variety of intrinsic structure, ranging from mostly prolate to mostly oblate, but that the characterization of their shapes as triaxial is most general. The interested reader is referred to the fine reviews on this subject for further details.

## 3 Dynamics and Stellar Population

That the global optical parameters of gE galaxies —  $r_e$ ,  $I_e$  — form a plane within the volume defined in conjunction with central velocity dispersion ( $\sigma_c$ ) is *prima facie* evidence that a strong relationship must exist between the stellar populations of gE galaxies and their dynamics (cf. discussion by Renzini & Ciotti [23]).

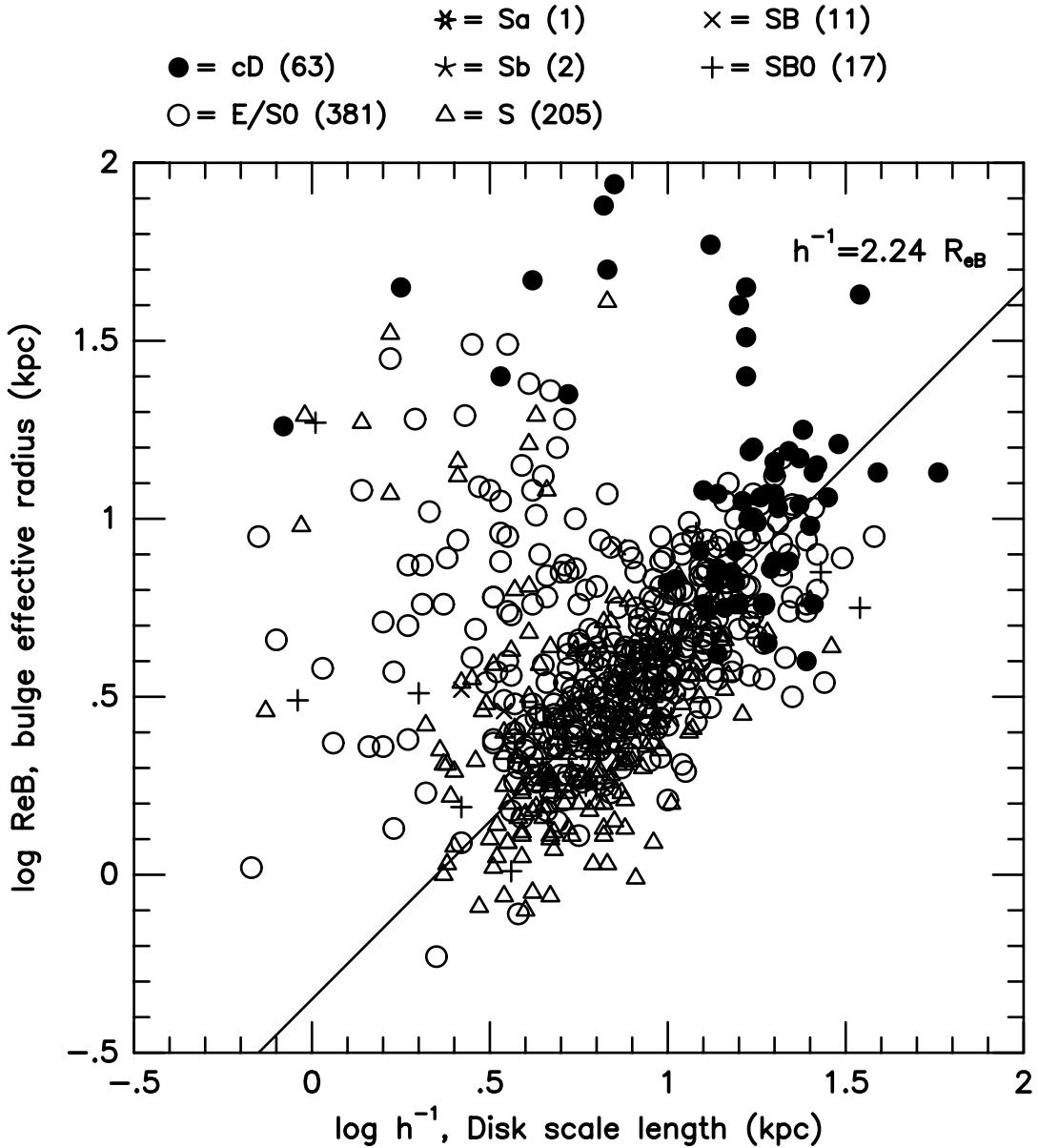
Bender, Burstein & Faber ([3]) extended this evidence to dwarf elliptical and dwarf spheroidal galaxies by comparing central measures of the line index  $Mg_2$  and  $\sigma_c$  for gE, dE and spiral bulges with more global values of  $[Fe/H]$  (transforming this to  $Mg_2$  via the relationship given in [11] for Galactic globular clusters) and  $\sigma$  for dSph. As shown in Figure 3 of [3], the relationship  $Mg_2 = 0.20 \log \sigma - 0.166$  fits well all of these early-type systems, from the  $10^{12} M_\odot$  gE galaxy to the  $10^5 M_\odot$  dSph.

Colless et al. [12] used our EFAR data to show that the  $Mg_2 - \sigma$  relationship is the same, within the errors, among 423 galaxies in 84 different galaxy groups and clusters. Moreover, in that paper it is possible to derive an *intrinsic* variation of  $Mg_2$  on  $\sigma$  (as opposed to error-caused) of 0.016 mag.

Without going into the subtleties of how the  $Mg_2$  index is related to stellar population, these empirical relationships establish a strong connection among the stellar populations of galaxies spanning a range of  $10^7$  in mass. To this writer, the fact that all of these “dynamically hot” stellar systems have stellar populations related to their internal dynamics *and to one another* is one of the central puzzles that any theory of galaxy formation must solve to be successful. There are currently two ideas that have been proposed as an overall framework to interpret these correlations (modulo our current lack of understanding of the physics of forming the stellar initial mass function):

Franx & Illingworth ([17]) suggest that the central gravitational potential determines the stellar population of a galaxy. However, this would require that stellar populations of gE galaxies be dependent on both  $\sigma$  and  $r_e$ , a prediction not consistent with the study of [3]. From their analysis, Bender et al. ([3]) derive that the stellar population is related to both the mass density ( $\rho$ ) of the galaxy *and* to its overall mass ( $M$ ), in the form  $M^2\rho$ . Bender et al. use this relation to predict that stellar population gradients within galaxies are small ( $\delta(B - V) \propto 0.037 \log \rho$ ). Unfortunately, such a prediction is hard to confirm, as small stellar population gradients are difficult to measure in the face of systematic problems in the measurements (e.g., differing seeing radii on images in different passbands; sky subtraction issues).

Figure 1: Log  $h^{-1}$  vs. Log ReB for EFAR Galaxies with Disks



Also related to this issue is the fact that [29] find the strength of the Balmer absorption line H $\beta$  in the spectra of gE galaxies is related to optical evidence of recent interactions with other galaxies. This leaves open the issue that any stellar population dispersion among gE galaxies at a given dynamical parameter can be due to residual effects of the most recent star formation event linked to the most recent interaction event.

#### 4 The Paradigm Shifts: Find a gE Galaxy without a Disk!

The separation of galaxies into gE and S0 classes is based primarily on the optical appearances of the galaxies. By these morphological definitions, S0 galaxies are diffuse in appearance (i.e., no obvious signs of active star formation) and show evidence of a disk; gE galaxies show no optical evidence of a disk, but are otherwise similar in appearance as S0's.

As pointed out by the first systematic study of S0 disk-to-bulge ratios ([8], [9]), one can hide a disk within a gE galaxy if the disk-to-bulge ratio is small enough (typically, 0.1 or less) and the disk is not oriented edge-on to the line-of-sight. However, it was not until the advent

of CCD imaging that the signal-to-noise of galaxy images became high enough that faint disks in morphologically-classified gE galaxies could be easily found from direct images.

Davies et al. ([14]) gave the first hint that many gE galaxies contain disks by pointing out that the ratio of rotational-to-anisotropic motions in gE galaxies is related to absolute luminosity: The proportion of galaxies that are primarily supported by anisotropic velocity dispersions increases with increasing galaxy luminosity. R. Bender and his colleagues ([4], [5]) then used the more accurate CCD data to define shape parameters for a large sample of gE galaxies via deviations of their image from a pure elliptical shape. Based on these kinds of analyses, both they and others have shown we can divide gE galaxies into two general classes: boxy and disky. As shown in a number of studies (cf. [2], [3]), disky gE galaxies tend to be less luminous than boxy gE galaxies, albeit with a substantial amount of crossover.

Saglia, Bender & Dressler [26]) found that gE galaxies with isophotes classified as “disky” define fundamental planes parallel to, but offset towards slightly lower M/L from that defined by “boxy” isophotes. They interpret this offset as due to the importance of rotation in determining the mass of disky galaxies which is not taken into account by just using central velocity dispersion for the mass calculation.

Our EFAR survey [27], [28]) obtained CCD and photoelectric photometry for 776 galaxies originally classified by eye on the Palomar Sky Survey prints as being gE candidates with axial ratios mostly face on ( $b/a > 0.4$ ). Of the 537 non-barred early-type galaxies in this sample (the sample was purposefully oversampled with spiral galaxies), 444 (83%) are classified as photometrically having evidence of a disk: E/S0, S0 or cD. In almost all cases this was done with multiple images for each galaxy, via a careful disk/bugle deconvolution procedure that properly took into account seeing radius and sky subtraction issues (cf. [27], [28]). The reader is referred especially to the 32 graphs of luminosity profiles for each galaxy in our survey presented in [28].

The extensive simulations done in [27] show that for any gE galaxy in which the disk is of similar surface brightness as the bulge, but of less than 10% the luminosity of the bulge, the disk is essentially invisible in the data we have. This is similar to the conclusion reached by [8] from analyzing the data on S0 galaxies.

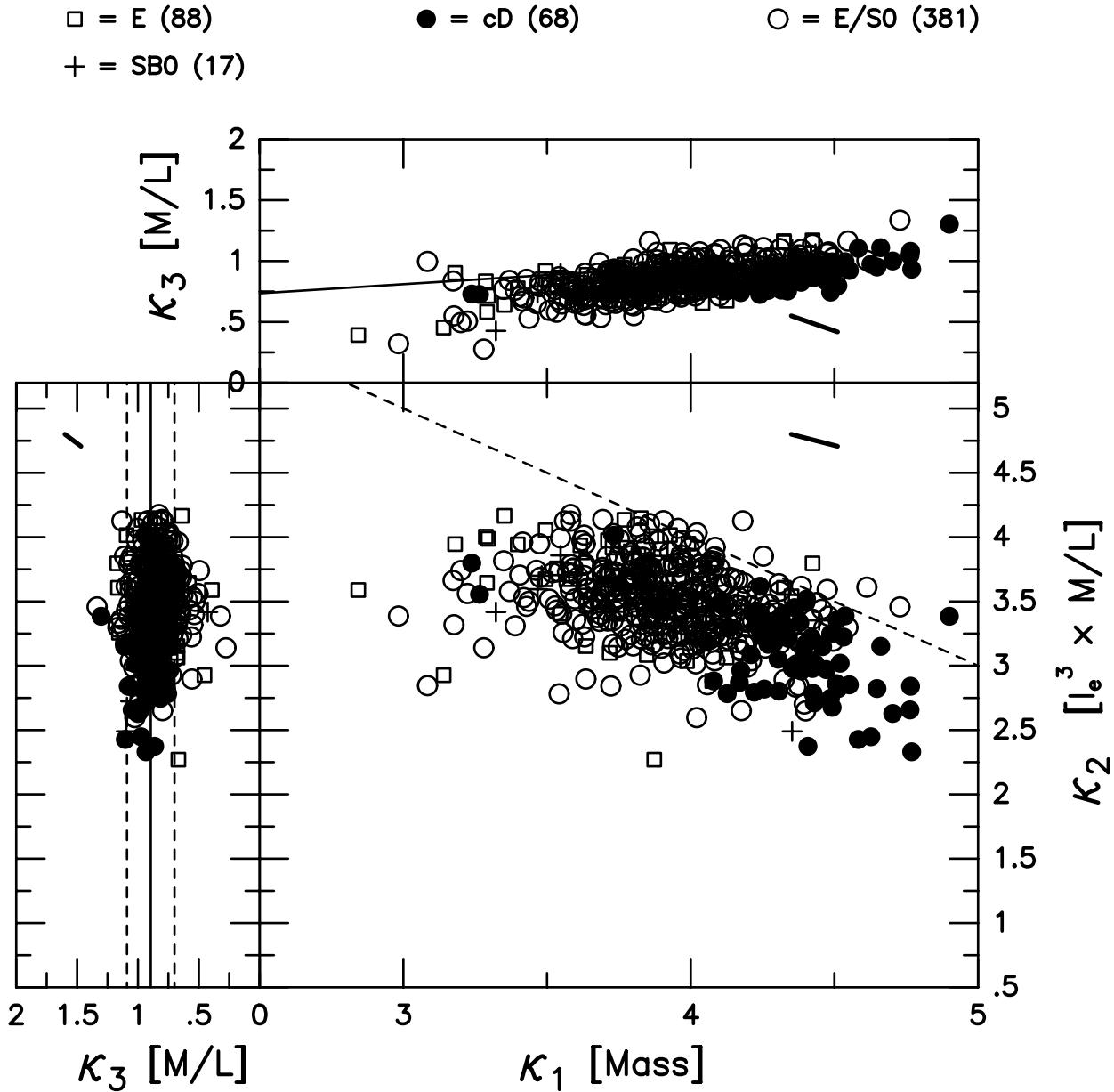
To go one step further, in our EFAR data we have looked for correlations among the disk and bulge parameters we have derived for these galaxies. The most interesting correlation we have found is between the exponential scale length of the disk ( $h^{-1}$  from the definition  $I(r) \propto e^{-hr}$ ) and the de Vaucouleurs  $R^{1/4}$ -law effective radius of the bulge ( $R_{eB}$ ) for those galaxies in our sample that have disks: 63 cD’s, 381 S0’s, 17 SB0’s, 208 non-barred spirals, and 11 barred spirals - 680 disk galaxies in all. Figure 1 shows this relationship for these galaxies, with different plotting symbols used for each galaxy type, as indicated in the figure.

As is evident, most of the 652 unbarred, disky galaxies, including all galaxy types (cD, E/S0, S0 and spiral), show a good relationship between disk scale length and bulge effective radius of the form  $h^{-1} \propto 2.24R_{eB}$  (with effective disk radius,  $R_{eD} = 1.68h^{-1}$  for an exponential disk). This is consistent with what has been found from other studies of bulge and disk parameters for late-type spiral galaxies ([13]).

The larger scatter about this relationship is preferentially to one side for all galaxies — smaller disk scale lengths for a given bulge effective radius. Based on the scatter in the general relationship to the opposite side (i.e., large disk size for a given bulge size), we separate out 73 disks in non-barred, non-cD galaxies that are more than 0.45 dex too small for their bulge sizes from the rest of the sample. We will tentatively term these disks as “interior disks,” as we find them in the interiors of galaxy bulges. These 73 galaxies are close to 10% of the 745 non-barred galaxies in our whole sample (i.e., including 88 gE and 5 cD galaxies in which we see no photometric evidence of a disk).

It is also evident upon inspection that these “interior disks” have preferentially small disk scale lengths when present, generally 3 kpc or less. Further investigation shows that “interior disks” have systematically higher surface brightnesses, and reside in galaxies with systematically fainter bulge surface brightnesses, than do disks and bulges of galaxies whose bulge and disk scale lengths fit the general relation. The combination of high surface brightness interior disk and low surface brightness bulge makes the interior disks easier to find. Thus, our photometry has uncovered evidence that at least 10% of E, E/S0, S0 and spiral galaxies contain within them small, high surface brightness disks, including five galaxies (NGC 4887, NGC 4839, Dressler 136, IC 4051 and IC 4052) in the Coma cluster. Significantly, one of these Coma cluster galaxies (IC 4051) has been shown by [19] to have a kinematically distinct, high surface brightness disk well inside its bulge.

**Figure 2: R-Band  $\kappa$ -space for EFAR E, cD and S0 Galaxies**



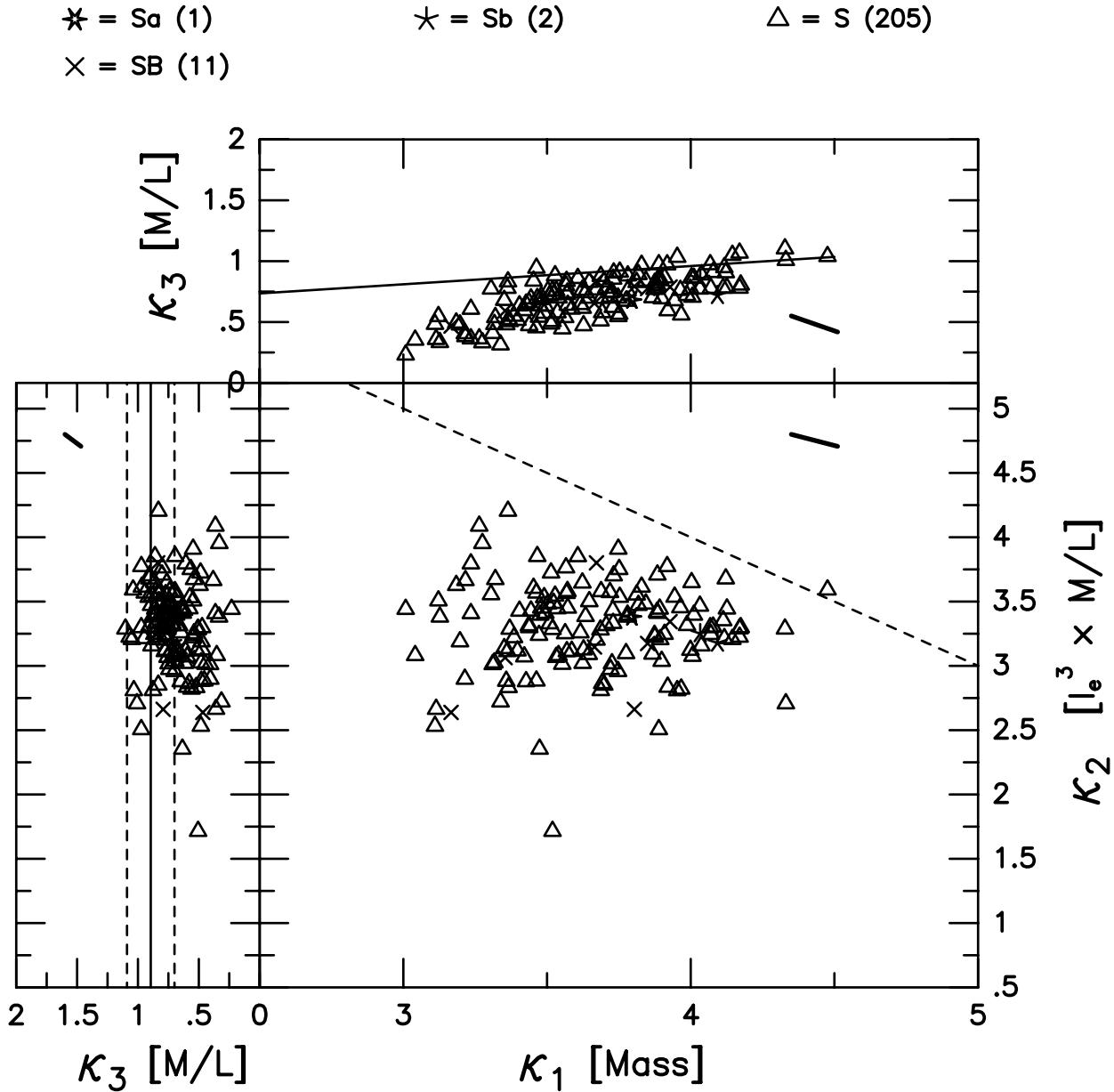
The EFAR survey preferentially selected more face-on galaxies as gE candidates, yet found nearly 85% of them have disks that can be detected photometrically. Given that the remaining gE galaxies *without* detected disks could still have disks contributing less than 10% of their luminosities, it is highly possible that *all gE galaxies contain disks*. If this is so, then as the

title of this section states, the paradigm shifts from “find a gE galaxy with a disk” to “prove that any gE galaxy *does not have* a disk!”

## 5 Elliptical Galaxy and Disky Galaxy Dynamics are Likely Related

One can unambiguously define the same set of three global parameters for all galaxies that go into defining the elliptical galaxy fundamental plane: effective radius, effective surface brightness and central velocity dispersion. As shown in [10], when you define these three global properties for spiral galaxies, irregular galaxies and elliptical galaxies in a self-consistent manner, we find that the physical properties of these galaxies are related to each other.

**Figure 3: R-band Kappa–space for EFAR Spiral Galaxies**



Burstein et al. ([10]) used the existing B-band data for these kinds of galaxies to define their relationships within  $\kappa$ -space. In Figures 2 and 3 we graphically show the analogous relationships we form from the EFAR R-band data for the gE, E/S0, cD and spiral galaxies in our sample. (The number of galaxies per type is different from that given in Figure 1 owing

to the additional requirement of velocity dispersion measurements.) As first discovered by [10], galaxies of different morphological class define distinct sequences with  $\kappa$ -space for B-band luminosity-related properties. Figures 2 and 3 show that these sequences are also seen within R-band-defined  $\kappa$ -space. The small solid lines drawn in each plane represent the effect of  $\pm 30\%$  distance errors. The solid line draw in the  $\kappa_3-\kappa_1$  plane is the edge-on view of the fundamental plane in the B-band. The dashed line in the  $\kappa_2-\kappa_1$  is the leading edge of the zone of exclusion seen in the B-band (cf. [10]). As with the B-band data, the fundamental plane is seen most edge-on in the R-band  $\kappa_3-\kappa_1$  ( $M/L$  vs.  $M$ ) plane and a well-defined zone of exclusion of the form  $\kappa_1 + \kappa_2 = \text{const}$  exists within the R-band  $\kappa_2-\kappa_1$  plane. Comparing Figures 2 and 3, we also see that, as in the B-band data, spiral galaxies in the  $\kappa_2-\kappa_1$  plane lie parallel to, but farther away from the zone of exclusion line than do earlier-type galaxies. As discussed in detail in [10], this evidence strongly suggests that all galaxies, gE to irregular, are formed in similar ways.

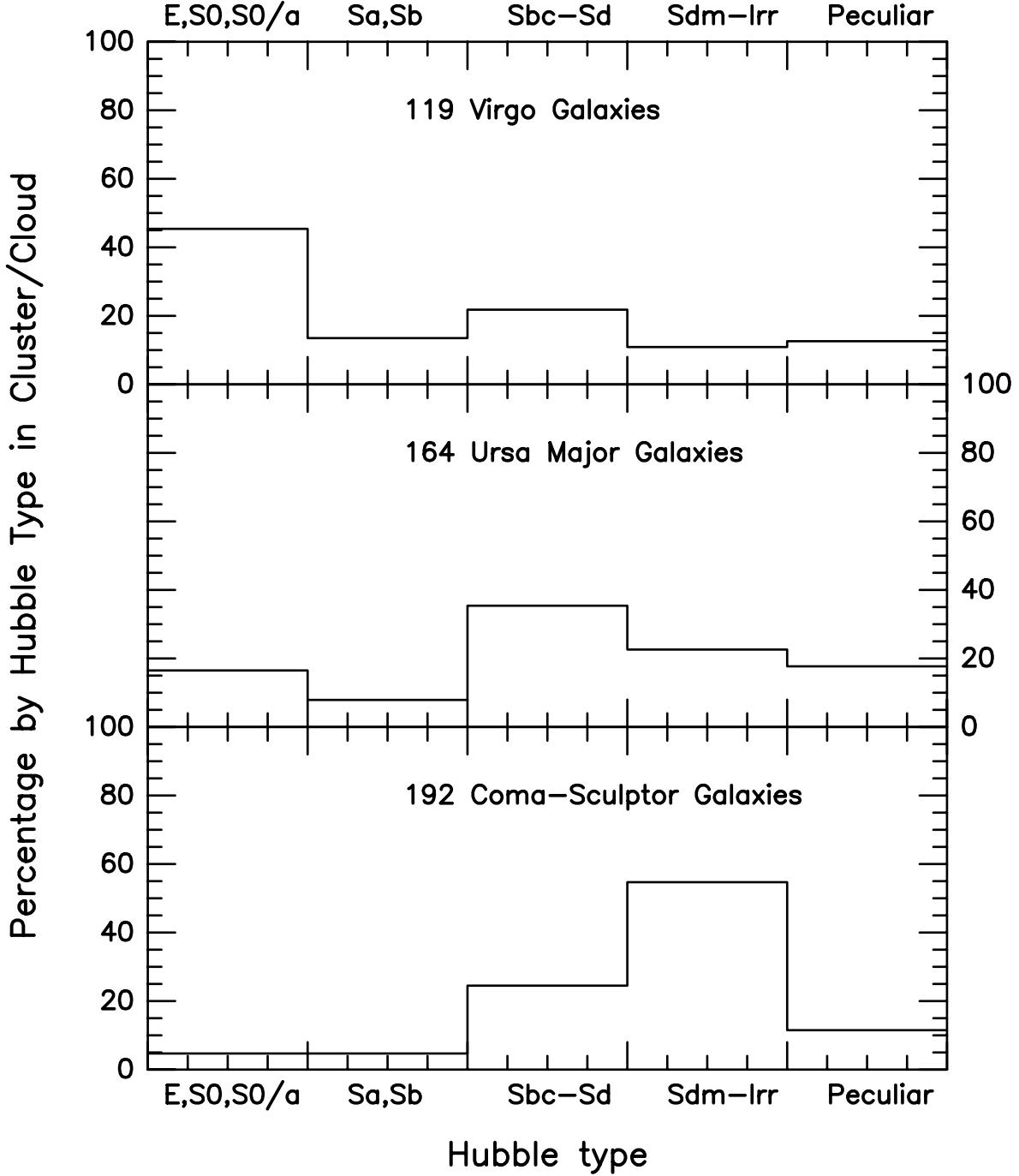
## 6 Nearby Galaxies are Morphologically-Segregated on 15-Mpc Size Scales

It has been well known for many years that gE galaxies tend to be found within highly populated, dense clusters. This trend was first quantified by [16], who showed that the percentage of early-to-late type galaxies is a function of the local density of galaxies around them. Early-type galaxies tend to dominate in number in high density regions of space, while late-type galaxies tend to dominate in number in low density regions.

Using data from the *Nearby Galaxies Catalog* of Tully ([30]), we have selected three regions of size 1000–1500 km/sec (14–20 Mpc if  $H_0 = 70 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ ) near our Local Group — the Coma-Sculptor cloud (in which our Local Group resides), the main part of the Virgo cluster, and the Ursa Major Cluster. Using the Hubble types given in the Tully catalog, we calculate the fraction of *giant* galaxies (i.e., not dwarfs) as found in each of these three regions of space, divided by type into five classes: E–S0/a, Sa–Sb, Sbc–Sd, Sd–Irr and Peculiar. The results are shown in terms of percentages of each type in Figure 4.

It is evident that late-type galaxies dominate the whole of the Coma-Sculptor Cloud, which is about 1500 km sec $^{-1}$  long and very narrow. In contrast, early-type galaxies comprise more than half of the giant galaxies in the Virgo cluster, while Ursa Major galaxies distribute themselves rather evenly among all five morphological classes. In all three cases, the morphological types of galaxies are related to each other over wide regions of space.

**Figure 4:**  
**Hubble type Distribution in 3 Nearby, Large-Scale Environments**



## 7 Discussion

The current paradigm for forming galaxies is that of hierarchical, clustering, merging (HCM) growth of galaxies with increasing age of the Universe. In this picture, the initial density fluctuations in the early universe grow gravitationally from small masses to large masses as the Universe expands. As discussed in [10], the distribution of the global properties of galaxies within  $\kappa$ -space is consistent with an HCM interpretation, if one associates the initial density of a galaxy with a specific range of Hubble types. In this picture, denser initial densities lead

to earlier Hubble types, on average. The HCM scenario is also consistent with what we know about the internal structures of E and S0 galaxies, if one allows (cf. [2]) the more luminous gE galaxies to form from mostly stellar mergers, while less luminous gE galaxies form from more gaseous mergers. Thus, the HCM scenario naturally leads to the observed relationships among galaxy dynamics from gE to Irr.

However, the HCM paradigm tells us nothing of how to change gas into stars, so cannot tell us the origin of the tilt of the galaxy fundamental plane in M/L vs. L, nor why stellar population should be so tightly related to galaxy dynamics in early-type galaxies. It also tells us nothing about any *a priori* initial conditions in the Universe that might lead to large-scale (1000-1500 km sec<sup>-1</sup> sizes as seen today) density fluctuations. In the face of current lack of input physics into both of these issues, we can speculate on how these relationships might be made.

This author believes that the stellar population-dynamical relation among early-type galaxies over a range of  $10^7$  in galaxy mass pins the initial subunit size in the HCM picture to be, at most, 1/2 to 1/5 the size of the smallest dSph, or about  $10^5$  M<sub>⊙</sub> in size. One possible scenario to generate the observed stellar population-dynamics relationship (certainly not the only one!) is this: A typical dSph will have 5-10 of these subunits in it, while a typical gE has  $10^5$ - $10^6$  subunits in it. If we then link the density ranges of the subunits to the mass of the galaxy in which they will reside (more mass, higher mean subunit density), and the stellar populations of the subunits to their densities, we can get the observed relationships. If this scenario is correct, it would also require that the subunits do not arbitrarily combine to form galaxies, but that most subunits “know” the kind of galaxy that they will combine to form.

The close spatial proximity and large-scale differences in galaxy types and, by the HCM paradigm, in initial mass densities, is a challenge for N-body modellers to reproduce. If these features in the observable universe can be reproduced in existing models, it will be triumph for those models. If, however, the models cannot reproduce such large-scale variations in mass density, one is left looking for other answers.

Finally, lest one be left with the impression that we have covered all issues relevant to galaxy formation here, consider just two other pieces of information we have to add to the mix: ubiquitous central supermassive blackholes in bulges (e.g., [20], [24]), and thermally-emitting X-ray gas of mass generally comparable to that in the galaxies themselves existing within galaxy clusters and groups (e.g., [22]).

Taken together, our knowledge of galaxy properties and their relationships to each other and to their environment has now become so detailed that we can well constrain any proposed model of galaxy formation. However, we lack a key ingredient as important to understanding galaxy formation as nuclear fusion was to understanding stellar evolution: Why a well-defined stellar initial mass function should exist, and the physics that is required to produce it. In absence of the knowledge of such physics, our modeling of galaxy formation will continue to be incomplete.

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